ECE 371
Materials and Devices

10/08/19 - Lecture 13

Intrinsic and Extrinsic Semiconductors

General Information

- Homework 4 assigned, due Tuesday 10/15
- Homework 3 solutions posted
- Midterm solutions posted
- Reading for next time: 4.3-4.5

Equilibrium Carrier Concentrations

Thermal Equilibrium: no external forces (e.g., voltages, electric fields, magnetic fields, temperature gradients, act on the semiconductor. Properties are time independent.

Equilibrium electron and hole concentrations:

$$n_0 = N_c \, exp\left[\frac{-(E_c - E_F)}{kT}\right]$$

$$p_0 = N_v \, exp\left[\frac{-(E_F - E_v)}{kT}\right]$$

Effective density of states:

$$N_c = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{\frac{3}{2}}$$

$$N_v = 2\left(\frac{2\pi m_p^* kT}{h^2}\right)^{\frac{3}{2}}$$

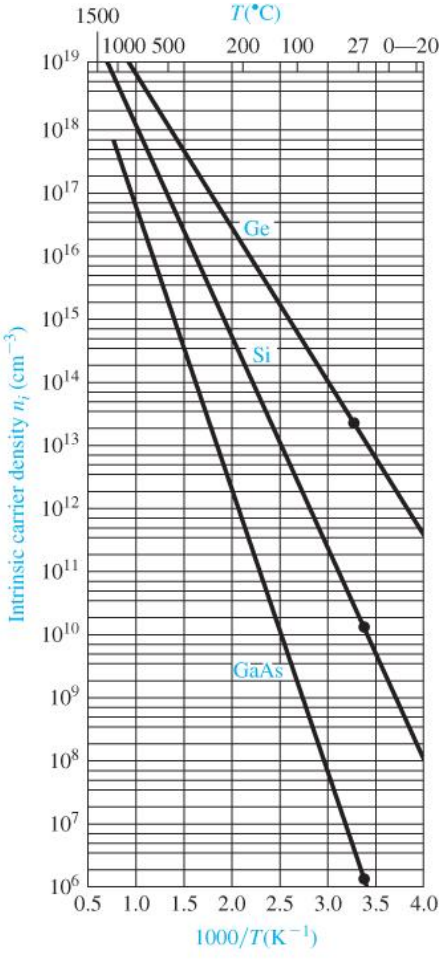
	N_c (cm^{-3})	N_v (cm^{-3})	m_n^*/m_0	m_p^*/m_0
Si	2.8e19	1.04e19	1.08	0.56
GaAs	4.7e17	7.0e18	0.067	0.48
Ge	1.04e19	6.0e18	0.55	0.37

Intrinsic Carrier Concentration

- Intrinsic semiconductor: no impurities
- # electrons in conduction band = # holes in valence band
- n_i is the intrinsic carrier concentration
- E_{Fi} is the intrinsic Fermi level
- E_g is the band gap energy

$$n_i^2 = N_c N_v \, exp\left[-\frac{E_g}{kT}\right]$$

T = 300 K	E_g (eV)	n_i (cm^{-3})
Si	1.12	1.5e10
GaAs	1.42	1.8e6
Ge	0.66	2.4e13



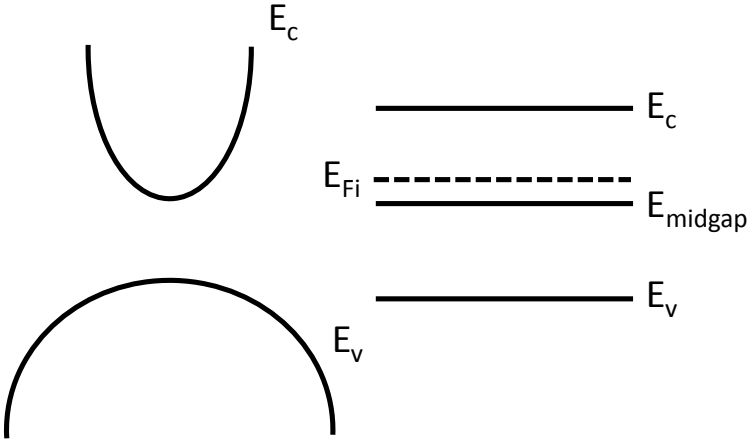
Intrinsic Fermi Level (E_{Fi})

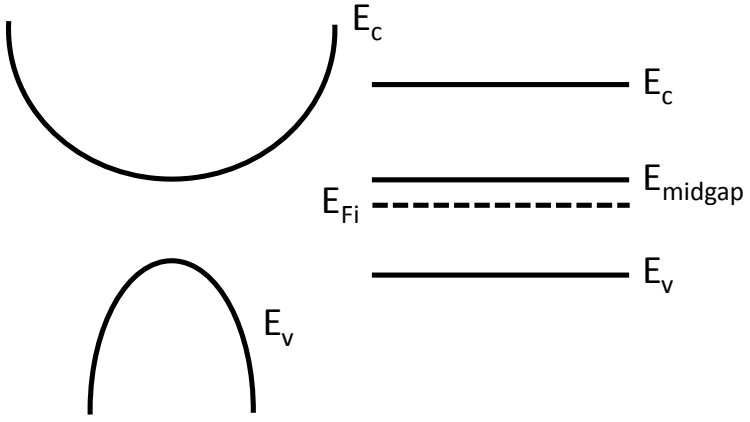
$$E_{Fi} - E_{midgap} = \frac{3}{4} kT \, ln\left(\frac{m_p^*}{m_n^*}\right)$$

$m_n^* = m_p^* \Rightarrow E_{Fi}$ is at midgap

$m_n^* < m_p^* \Rightarrow E_{Fi}$ is above midgap

$m_n^* > m_p^* \Rightarrow E_{Fi}$ is below midgap





E_{Fi} must shift away from the band with the higher DOS (m*) to maintain $n_0 = p_0$

Extrinsic Semiconductors (n-type)

- Extrinsic Semiconductor: addition of intentional impurities (dopants) to control conduction properties
- N-type semiconductors primarily conduct current using electrons in the conduction band
- In silicon, a phosphorus (P) atom donates an electron to the lattice → *"donor"*
- P is group V and uses 4 valence electrons to bond with silicon
- The last valence electron is weakly bound to the phosphorus atom and can be elevated to the conduction band (i.e. – unbound from the P atom) with some thermal energy

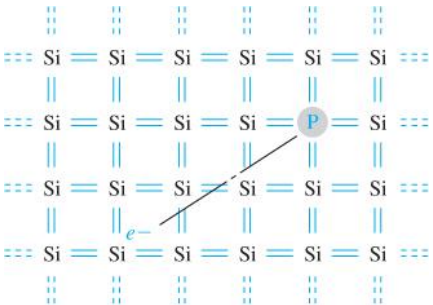


Figure 4.4 | Two-dimensional representation of the silicon lattice doped with a phosphorus atom.

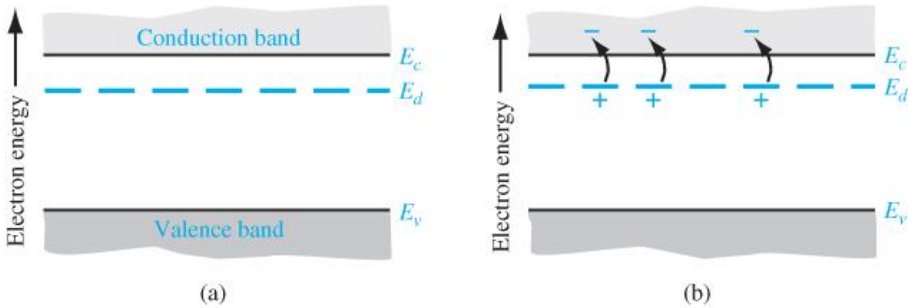


Figure 4.5 | The energy-band diagram showing (a) the discrete donor energy state and (b) the effect of a donor state being ionized.

Extrinsic Semiconductors (p-type)

- P-type semiconductors primarily conduct current using holes in the valence band
- In silicon , a boron (B) atom accepts an electron from the lattice → *"acceptor"*
- B is group III and uses 3 valence electrons to bond with silicon
- It takes an additional valence electron from the lattice, leaving a hole
- Removal of an electron from the lattice requires some thermal energy
- The empty state left behind can propagate through the crystal and generate current

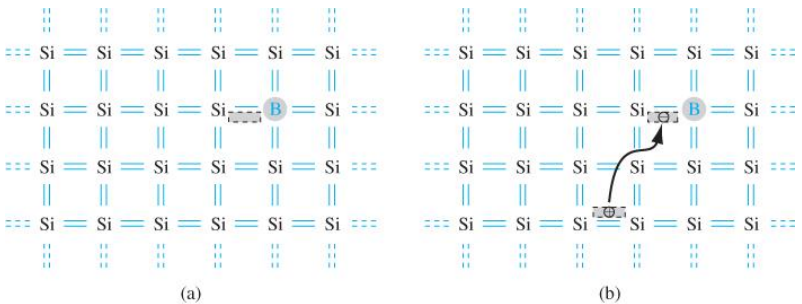


Figure 4.6 | Two-dimensional representation of a silicon lattice (a) doped with a boron atom and (b) showing the ionization of the boron atom resulting in a hole.

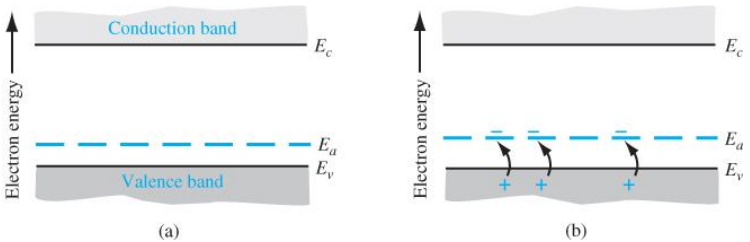


Figure 4.7 | The energy-band diagram showing (a) the discrete acceptor energy state and (b) the effect of an acceptor state being ionized.

Ionization Energy

- Energy required to remove a weakly bound electron from the lattice and put it in the conduction band is called "*ionization energy*"
- Similarly, the energy required to elevate an electron from the lattice into an acceptor level also has an ionization energy (holes)
- Some dopants can function as donors AND acceptors. These are called *amphoteric dopants*. An example is a Si dopant in a GaAs lattice.

Table 4.3 | Impurity ionization energies in silicon and germanium

Impurity	Ionization energy (eV) Si	Ge
Donors		
Phosphorus	0.045	0.012
Arsenic	0.05	0.0127
Acceptors		
Boron	0.045	0.0104
Aluminum	0.06	0.0102

Table 4.4 | Impurity ionization energies in gallium arsenide

Impurity	Ionization energy (eV)
Donors	
Selenium	0.0059
Tellurium	0.0058
Silicon	0.0058
Germanium	0.0061
Acceptors	
Beryllium	0.028
Zinc	0.0307
Cadmium	0.0347
Silicon	0.0345
Germanium	0.0404

Extrinsic Semiconductors (Fermi Level)

- Addition of dopant atoms changes the position of the Fermi energy
  - For $E_F > E_{Fi} \rightarrow n > p \rightarrow$ n-type
  - For $E_F < E_{Fi} \rightarrow p > n \rightarrow$ p-type

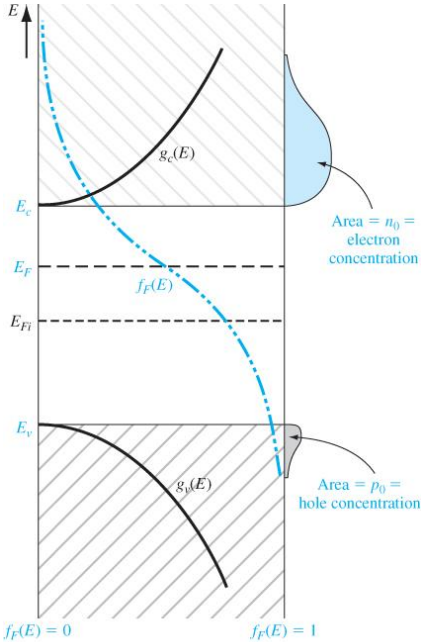


Figure 4.8 | Density of states functions, Fermi–Dirac probability function, and areas representing electron and hole concentrations for the case when E_F is above the intrinsic Fermi energy.

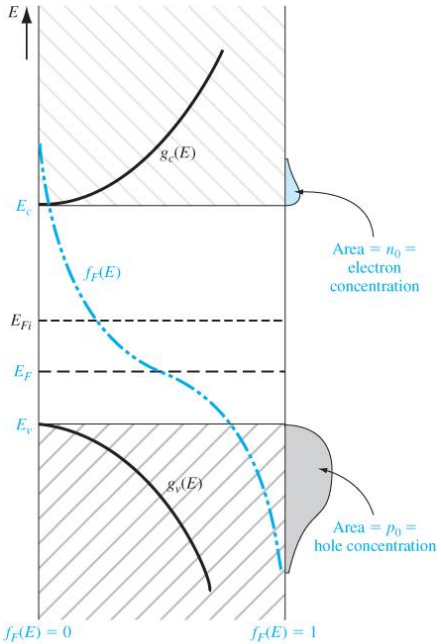


Figure 4.9 | Density of states functions, Fermi–Dirac probability function, and areas representing electron and hole concentrations for the case when E_F is below the intrinsic Fermi energy.

$$n_0 = n_i \, exp\left[\frac{E_F - E_{Fi}}{kT}\right]$$

$$p_0 = n_i \, exp\left[\frac{-(E_F - E_{Fi})}{kT}\right]$$

The $n_0 * p_0$ Product

- The product of n_0 and p_0 is always a constant for a given material at a given temperature
- The following relationship was derived under the Boltzmann approximation

$$n_0 \, p_0 = n_i^2$$

Degenerate Semiconductors

- *Nondegenerate* – individual dopant atoms are far apart and do not interact. Spacing between dopants is large.
- *Degenerate* – concentration of dopant atoms is high and individual dopant atoms interact, splitting the dopant energies into a band.
- E_F can move into the conduction or valence band if $n_0 > N_c$ or $p_0 > N_v$, respectively. This leads to a large electron or hole concentration.

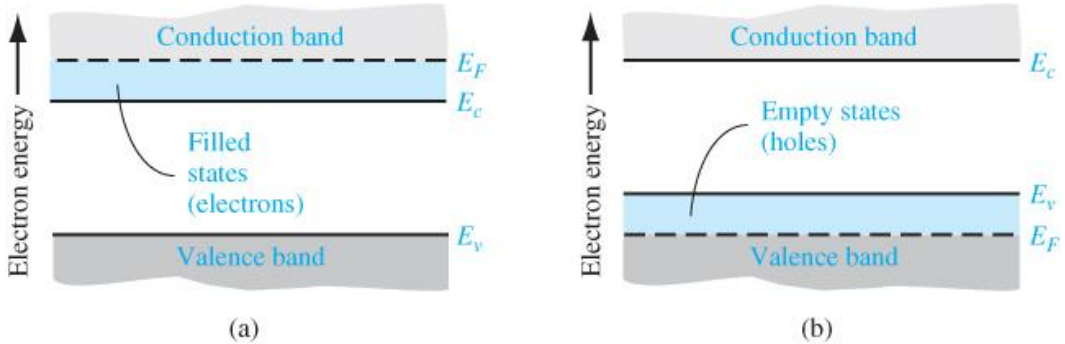


Figure 4.11 | Simplified energy-band diagrams for degenerately doped (a) n-type and (b) p-type semiconductors.

Exercise Problem 4.5

EXERCISE PROBLEM

Ex 4.5 Determine the thermal-equilibrium concentrations of electrons and holes in silicon at $T = 300$ K if the Fermi energy level is 0.215 eV above the valence-band energy E_v. (Ans. $p_0 = 2.58 \times 10^{15}$ cm^{-3}, $n_0 = 1.87 \times 10^4$ cm^{-3})

Donor/Acceptor Statistics

- Pauli exclusion principle applies to donors and acceptors
- n_d and p_a are the electron and hole concentrations in donor and acceptor states, respectively
- E_d and E_a are the donor and acceptor energy levels, respectively
- Factors of ½ and ¼ are $1/g$, where g is the degeneracy factor

$$n_d = \frac{N_d}{1 + \frac{1}{2} exp\left[\frac{E_d - E_F}{kT}\right]} = N_d - N_d^+$$

Electrons in donor states

$$p_a = \frac{N_a}{1 + \frac{1}{4} exp\left[\frac{E_F - E_a}{kT}\right]} = N_a - N_a^-$$

Holes in acceptor states